Surface Emissivity Impact on Temperature and Moisture Soundings from Hyperspectral Infrared Radiance Measurements

ZHIGANG YAO, JUN LI, JINLONG LI, AND HONG ZHANG

Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

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ABSTRACT

An accurate land surface emissivity (LSE) is critical for the retrieval of atmospheric temperature and moisture profiles along with land surface temperature from hyperspectral infrared (IR) sounder radiances; it is also critical to assimilating IR radiances in numerical weather prediction models over land. To investigate the impact of different LSE datasets on Atmospheric Infrared Sounder (AIRS) sounding retrievals, experiments are conducted by using a one-dimensional variational (1DVAR) retrieval algorithm. Sounding retrievals using constant LSE, the LSE dataset from the Infrared Atmospheric Sounding Interferometer (IASI), and the baseline fit dataset from the Moderate Resolution Imaging Spectroradiometer (MODIS) are performed. AIRS observations over northern Africa on 1–7 January and 1–7 July 2007 are used in the experiments. From the limited regional comparisons presented here, it is revealed that the LSE from the IASI obtained the best agreement between the retrieval results and the ECMWF reanalysis, whereas the constant LSE gets the worst results when the emissivities are fixed in the retrieval process. The results also confirm that the simultaneous retrieval of atmospheric profile and surface parameters could reduce the dependence of soundings on the LSE choice and finally improve sounding accuracy when the emissivities are adjusted in the iterative retrieval. In addition, emissivity angle dependence is investigated with AIRS radiance measurements. The retrieved emissivity spectra from AIRS over the ocean reveal weak angle dependence, which is consistent with that from an ocean emissivity model. This result demonstrates the reliability of the 1DVAR simultaneous algorithm for emissivity retrieval from hyperspectral IR radiance measurements.

1. Introduction

Atmospheric Infrared Sounder (AIRS) data have been shown to be significant to atmospheric research and to monitoring the earth’s environment (Chahine et al. 2006). Infrared (IR) land surface emissivity (LSE) must be taken into account to improve the accuracy of boundary layer temperature and moisture profiles and land surface temperature (LST) in the retrieval process from AIRS radiance measurements that are based on a radiative transfer model. Simulation analysis indicates that LSE plays an important role in the retrieval of surface skin temperature and terrestrial boundary layer moisture from AIRS (Li et al. 2007; Liu et al. 2008; Jin and Li 2010). Accurate LSE is also essential to help to better assimilate high-spectral-radiance measurements into numerical weather prediction (NWP) models over land. So far, hyperspectral IR radiance measurements over land have not been widely used in operational NWP models (Collard et al. 2010).

LSE for a given spectral channel is often fixed or is obtained from a database when assimilating radiances over land. Also, the emissivity is usually not updated simultaneously along with the profiles in the physical iterative retrieval (Li et al. 2000; Zhou et al. 2006). To improve LST and atmospheric sounding retrievals from current and future IR sounders, global IR LSE datasets have been derived by numerous researchers (Seemann et al. 2008; Li and Li 2008; Péquignot et al. 2008; Zhou et al. 2008, 2010). For example, Seemann et al. (2008) have improved the LSE with a synthetic regression-based surface emissivity scheme derived from a training database. Li et al. (2007) developed techniques to separate surface skin temperature and surface emissivity by representing the emissivity spectrum as eigenvectors (EV) derived from laboratory spectra in a one-dimensional variational (1DVAR) approach, and global high-spectral-resolution LSE spectra from AIRS radiance measurements were derived (Li and Li 2008). Zhou et al. (2008)
used an efficient synthetic regression approach to derive global LSE from AIRS. This approach is based on clear-sky radiances simulated from the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast and a surface emissivity training dataset, and LSE spectra from the Infrared Atmospheric Sounding Interferometer (IASI) have also been derived (Zhou et al. 2011) by the physically statistical approach.

Researchers have compared different IR LSE datasets (Moy et al. 2006; Péquignot et al. 2008; Zhou et al. 2008). Because it is difficult to have in situ LSE measurements for validation, the LSE evaluation is conducted by comparing laboratory measurements (Hulley et al. 2009; Zhou et al. 2011). The drawback is that laboratory measurements are only an approximation of the actual land situation without taking into account the coarse spatial resolution of current hyperspectral IR sensors. Another method developed by Li et al. (2010) involves comparing calculated brightness temperatures (BT), with LSE as input, with observed BTs for quantitatively evaluating the uncertainties of various LSE datasets in three IR window bands. The differences between the calculated and observed BTs could be due to inaccurate input of LST, atmospheric temperature, and moisture profiles, however, especially when applied to atmospheric absorption channels that are sensitive to surface. In addition, the impact of LSE uncertainties on using the hyperspectral IR sounding data over land has not been well addressed yet.

The primary purpose of this study is to investigate the impact of LSE datasets with different spectral resolutions on atmospheric sounding retrievals from AIRS. On the other hand, the dependence of the physical retrieval on the choice of emissivities will be evaluated. The study may also lead to an improvement in assimilating IR radiances in NWP models over land. The typical assumption of using constant LSE, datasets derived from the high-spectral-resolution sounder IASI, and baseline fit datasets (version 4.1) from the Moderate Resolution Imaging Spectroradiometer (MODIS) are used in the study.

The data and retrieval algorithm are introduced in section 2. The retrieval experiments and results are presented in section 3. The angle dependence of the emissivity is investigated with AIRS data over ocean in section 4. A summary is given in section 5.

2. Data and method

a. AIRS radiance measurements

The AIRS (Chahine et al. 2006), on the Earth Observing System (EOS) Aqua satellite, was launched on 4 May 2002 and is the first of a new generation of high-spectral-resolution IR sounders. AIRS has 2378 channels measuring outgoing radiances in three bands, 649–1136, 1217–1613, and 2181–2665 cm⁻¹ (8.8–15.4, 6.2–8.2, and 3.75–4.58 μm), at a spatial resolution of about 13 km (nadir). AIRS is able to sense atmospheric temperature, water vapor, trace gases, and surface skin temperature with high vertical resolution and accuracy. The AIRS instrument sweeps along its orbit gathering data, and the data are sectioned into pieces—each piece is called a granule. The spatial coverage of each AIRS data granule is roughly 2250 km × 1650 km.

b. IASI LSE dataset

Zhou et al. (2009, 2011) developed the physically statistical and 1D variational approach to simultaneously retrieve atmospheric thermodynamic and surface or cloud microphysical parameters from hyperspectral infrared sounders. It has been applied to the IASI to produce the global monthly mean land surface spectral emissivity with a spatial resolution of 0.5° latitude × 0.5° longitude. Initial emissivity validation with an all-seasonal global dataset shows that the standard deviation of difference for IASI emissivity accuracy from retrieval simulation is less than 0.02 and 0.04 for the longwave and shortwave window regions, respectively (Zhou et al. 2011). The LSE weekly-mean climatological data derived from IASI measurements will be available in the near future (D. K. Zhou, NASA Langley Research Center, 2010, personal communication); it is noted, however, that a preliminary research-test result of the monthly-mean IASI emissivity product is used in the following retrieval experiment.

c. University of Wisconsin BLF land surface emissivity

Seemann et al. (2008) derived a high-spatial- and moderate-spectral-resolution global database of LSE by using a procedure called the baseline fit (BLF) method. Based on an analysis of MODIS/University of California, Santa Barbara and Advanced Spaceborne Thermal Emission and Reflection Radiometer/Jet Propulsion Laboratory libraries, they extracted the most representative spectra (about 300) and identified 10 wavelengths (“hinge points”) situated within strategic regions of the emissivity spectrum. According to a conceptual model of LSE, the method adjusts a baseline emissivity spectrum based on “MOD11” LSE measurements. This approach captures the most important features of the emissivity spectrum. In their study, the impact of LSEs on atmospheric total precipitable water retrievals with MODIS radiance measurements has been evaluated over land. Substantial improvement was shown over traditional retrievals conducted
With the typical assumption of constant LSEs. The original BLF dataset provides monthly averaged global IR LSE spectra from 3.7 to 14.3 \( \mu m \) at a 0.05° × 0.05° spatial resolution based on the analysis of MODIS data (Seemann et al. 2008). To make this dataset closer to the IASI emissivity database in the spatial resolution, it is degraded to the 0.25° × 0.25° latitude–longitude grid scale in the following study.

d. Method

Because of the large number of unknowns in the inverse problem and the instability of the solution, it is usually difficult to retrieve emissivity spectrum and atmospheric parameters directly from hyperspectral-resolution IR radiances. Zhou et al. (2002) initially suggested and used EVs to represent a hyperspectral IR emissivity spectrum, which makes it possible to simultaneously derive emissivity spectrum and atmospheric parameters from hyperspectral IR radiances. Li et al. (2007) used a 1DVAR approach to extract the IR surface emissivity spectrum represented by its EVs obtained from laboratory measurements. This algorithm has been tested successfully with a typical AIRS granule over the Saharan region. In the following study, the same algorithm is used to investigate the effects of the different LSE datasets on AIRS sounding retrievals. The IASI- and MODIS-derived LSE climatological datasets mentioned above will be used as a priori (or guess) emissivities for the AIRS retrieval algorithm, which can be allowed to iterate on the emissivity (simultaneous retrieval) or not (fixed emissivity in iteration).

3. Retrieval experiments and results

To compare the effects of different LSE datasets on atmospheric parameter retrievals, two groups of experiments are performed. In each group, three retrieval experiments with different emissivities introduced above are conducted. The three different emissivity datasets are 1) a spectrally constant emissivity set to 0.98, 2) LSE from IASI, and 3) LSE from BLF. In the first group, the emissivities are fixed in the iterations. In the second group, the emissivities are updated simultaneously with temperature and moisture profiles in the iterations. The retrieval experiments are listed in Table 1. The IASI LSE in January 2008 and July 2007 as well as the MODIS-derived LSE in January and July 2007 will be used for the AIRS retrieval experiments in January and July 2007, respectively.

The experiments are performed with AIRS radiance measurements. The MODIS cloud mask is used to identify the AIRS clear footprints (Li et al. 2004). The atmospheric temperature and moisture retrievals are evaluated by comparison with the ECMWF temperature and moisture reanalysis profiles from the nearest grid point in space, which are temporally interpolated to the AIRS observation time. As a result, the retrieval comparison can be easily performed with a large variety of surface and atmospheric conditions. In the following study, the AIRS granule 019 over northern Africa for 5 January 2007 will be first used and analyzed in detail. This AIRS granule contains various surface types and includes sufficient cloud-free pixels.

For granule 019 on 5 January 2007, the water vapor mixing ratio retrievals (WR) from different experiments in group 1 (LSE fixed) and the ECMWF reanalysis at 852 hPa are shown in Fig. 1. The water vapor variation seems like a wave from the top left to the bottom right in the ECMWF water vapor map, which could help to better evaluate the retrieval accuracy. It can be seen that the distribution of the water vapor mixing ratio from the retrievals with the IASI LSE agrees better with the ECMWF reanalysis, although it contains a small uncertainty from the monthly mean climatological values being applied to the first-week measurements of the month and from the 0.5° × 0.5° latitude–longitude grid scale of the climatological data used in this analysis. The retrieval with the constant LSE of 0.98 obtains the worst results, most of which are overestimated because of the unreasonable LSE assumption. This confirms that the LSE has a significant impact on the WR from AIRS over land. In comparison with the ECMWF reanalysis, the root-mean-square differences (RMSE) from three 1DVAR experiments are shown in Fig. 2.

From Figs. 2a and 2b, it can be seen that the retrievals near the surface are sensitive to LSE when the emissivities are fixed in the iteration. Significant retrieval improvement using the LSE spectrum from IASI and BLF is shown over those made with the typical assumption of constant LSE (i.e., 0.98). It is also shown that the LSE from IASI appears to be more accurate for soundings in this particular case, especially for the WRs. This indicates that the IASI LSE dataset may be more reasonable than the BLF in hyperspectral IR sounding retrieval. It could be explained by the fact that the baseline fit LSE results from only six available wavelengths spanning three spectral regions (3.8–4, 8.6, and 11–12 \( \mu m \) in

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Table 1. Experiments with fixed emissivities and adjusting emissivities in the retrieval process.
FIG. 1. Comparison of retrieved WR (g kg\textsuperscript{-1}) in group 1 (fixed emissivity) and group 2 (adjusting emissivity) with ECMWF reanalysis at 852 hPa for granule 019 on 5 Jan 2007 overlaid on an 11-\textmu m brightness temperatures (K; black/white) image.
FIG. 2. Comparison of physical sounding retrievals over land with different LSE datasets for AIRS granule 019 on 5 Jan 2007 for (top) temperature and (bottom) water vapor. The lines represent the RMSE of the physical iterative retrievals with different LSE approaches (labels 0.98, IASI, and BLF correspond to the three experiments shown in Table 1) in comparison with the ECMWF reanalysis data. The (right) improvement represents the RMSE differences between (left) group 2 (fixed emissivity) and (center) group 1 (iterated emissivity).
the MODIS operational LSE product (MOD11). The spectral resolution of the BLF database is adequate in the window bands (Li et al. 2010), whereas the IASI LSE is good in the absorption spectral regions, which is suitable for hyperspectral radiance assimilation and application in NWP models. In addition, the quartz doublet at 8.6 μm is not well defined for MODIS data.

From Figs. 2c and 2d, it is noted that the initial LSE of 0.98 could obtain similar results with other LSE first-guess options in group 2 (emissivity iterated) for the temperature and moisture retrieval, although the results near the boundary layer from the BLF emissivities are slightly better than those from the IASI emissivities. The WRs at 852 hPa are also shown in Fig. 1. It can be seen that the differences between retrievals and ECMWF reanalysis are reduced in three experiments when the emissivity is updated simultaneously. This is caused by the fact that the adjusting process could make the different initial guesses approaching the only truth.

In addition, Figs. 2e and 2f show that the physical iterative retrieval with updating LSE obtains better results than that with the fixed LSE, especially for an LSE first guess of 0.98. It also indicates that the simultaneous retrieval of atmospheric and surface parameters could reduce the dependence of soundings on the choice of LSE and finally improve the sounding accuracy. This result shows the reliability of the algorithm, which could obtain comparable results even for a poor initial LSE first guess although it needs more iterative times. In addition, it is noted that the improvements for the IASI-derived LSE assumption are very small by comparison with the other two LSE assumptions. If the initial LSE is not good enough, the improvement should be greater with the simultaneously updating process. So, this result further supports that the LSE climatological values from IASI seem accurate enough for atmospheric parameter retrievals.

The mean initial and retrieved emissivity spectra from all clear pixels over land are shown in Fig. 3. As shown in Fig. 2b, when the LSEs are fixed in the physical retrievals, the WR using the IASI LSE could obtain significantly better results than that from the BLF LSE. This may be explained by the fact that the emissivities are more reasonable from IASI than from BLF in this particular case, especially in the water vapor absorption bands. Figure 3 indicates that the simultaneous sounding and emissivity retrieval method could make the final retrieved LSE spectra with different first guesses agree better, although there are still large differences in absolute magnitude in the shortwave region and in the quartz doublet. The significant changes in the emissivity spectrum for the first experiment correspond to the great sounding retrieval improvement shown in Figs. 2e and 2f. The initial and retrieved emissivities at 8.15 μm over land in the simultaneous physical retrieval are presented in Fig. 4. With the BLF LSE assumption, the changes in the middle section on the right-hand side of the images correspond to the improvement shown in Fig. 1. This indicates that the updated LSEs contribute to the improvement of the WR for this granule.

To validate further the conclusions drawn from the particular case analyzed above, experiments should be
FIG. 4. Initial and retrieved emissivities at 8.15 μm over land in the simultaneous physical retrieval for granule 019 on 5 Jan 2007 overlaid on an 11-μm brightness temperatures (K; black/white) image.
Fig. 5. As in Fig. 2, but for AIRS data for 1–7 Jan and 1–7 Jul 2007 over northern Africa.
performed with more granules in different seasons. The LSE feature over northern Africa is the strongest in the global. Li et al. (2010) have also shown that there are significant differences between IASI and BLF emissivity datasets in this area. These differences will benefit investigating the possible impacts of different surface emissivity datasets on the atmospheric parameter retrievals. So, the AIRS data with the latitudes of 0°–40°N and the longitudes of 20°W–40°E are selected for further investigation. There are more than 250 AIRS granules available over this domain on 1–7 January and 1–7 July 2007, which could be used to represent data in different seasons. The retrieval accuracies for all granules are shown in Fig. 5. The results are similar to what is shown in Fig. 2. Note that there are slight differences among different experiments when the LSE is updated in the retrieval. This reveals that the dependence of the atmospheric thermodynamic parameter retrieval on the choice of LSE seems weak if the LSE is retrieved simultaneously in 1DVAR.

4. Angle dependence on emissivity retrieval from hyperspectral IR sounder radiance measurements

The angle dependence of the emissivity from hyperspectral IR sounder observations has not been investigated before. The surface emissivity depends on the angle of incidence (Labeled and Stoll 1991; Smith et al. 1996; Wu and Smith 1997; Plokhenko and Menzel 2000). The measured emissivity spectrum obtained by Hanafin and Minnett (2005) also suggests that the surface emissivity over ocean is sensitive to view angles of >40°. The angle dependence of the surface emissivity could have impacts on the soundings for large view angles.

Because of the significant variability of the surface emissivity and Lambertian effects over land, it is very difficult to investigate the angle dependence of the emissivity by using AIRS observations over land. In this study, a preliminary investigation of angle dependence of the surface emissivity is performed over ocean. To evaluate the quality of the retrieved emissivity over ocean, a practical model developed by Nalli et al. (2008a) is used. This model is developed for remote sensing applications over ocean, which depend on sea surface wind speeds and incidence angles, and has been validated against an exhaustive set of Fourier transform spectrometer field observations acquired at sea (Nalli et al. 2008b). The emissivity lookup table is based on the Hale–Querry refractive and Cox–Munk wave slopes. The wind speed is set to 5 m s⁻¹ because the calculation shows that the wind dependence of the emissivity is weaker than the angular dependence.

For AIRS granule 046 on 5 September 2008, the observation background and retrieved emissivity at 11 μm by using the 1DVAR algorithm are shown in Fig. 6. The retrieved emissivity spectrum for all clear pixels is shown in Fig. 7. The emissivity spectrum from the model is also shown in this figure. The comparison demonstrates that the emissivities from the retrieval and the model in the window band between 800 and 950 cm⁻¹ agree well. Note also, however, that there are significant discrepancies for the absorption bands. The initial emissivity for the physical retrieval is based on a regression method, which takes advantage of spectral correlations to present an emissivity spectrum by its EVs. As a result, the initial emissivity spectrum should be partly dominated by EVs, which are obtained from training datasets for selected emissivity spectra mainly over land, especially for those channels that are not very sensitive to the surface emissions. As a consequence, the differences should be caused by the relatively low sensitivity of these channels to the surface.

In this study, an investigation of angle dependence of the surface emissivity is performed for 68 AIRS granules with the latitudes of 0°–40°N and the longitudes of 60°–30°W from 1 to 7 January 2007 over the Atlantic Ocean, which is one of the mostly cloud-free areas and allows us to get enough cloud-free pixels at each angle. The retrieved emissivities at 11 and 8.15 μm with the angle are presented in Fig. 8. It is known that cloud contamination is usually a systematic error that inevitably becomes more prevalent at larger angles, and so the upper envelope of the retrievals may better minimize their impact. To exclude possible cloud contamination, the 90th percentiles are shown. The results show that the angle dependence from the simulation and retrievals at
11 μm is weaker than that at 8.15 μm. At 8.15 μm, the emissivity decreases with the increase of the angle larger than 40°, which means that there exists an angle dependence of the surface emissivity. The retrieval appears even to capture the precise angle at which emissivities begin to decrease substantially. In addition, it is demonstrated that the emissivity variation with angle is not symmetric as expected. A possible explanation is that the observation may be nonsymmetric at this channel. To better investigate the differences, more studies should be performed in the future by using radio sounding data, which could be used to calculate more accurate sea surface emissivity spectra from AIRS observations.

5. Summary

The IR LSE is critical for better atmospheric sounding retrievals and radiance assimilation over land. Some methods have been developed to extract the IR emissivity spectra from satellite observations. To better understand the sensitivity of the sounding retrievals from hyperspectral infrared sounder data to different LSE datasets, a one-dimensional variational retrieval algorithm has been used to conduct experiments for the AIRS observations over northern Africa in different seasons. Overall, it is shown that the emissivity from IASI could help the sounding retrieval because of its full spectral coverage in the IR region, which makes the retrieval more accurate. In addition, it is demonstrated that the 1DVAR retrieval algorithm could improve the accuracy of AIRS sounding retrieval over land if the LSE is simultaneously retrieved. Although the LSE agreement among different datasets is not good, the 1DVAR retrieval with updating emissivities could make them agree better. The results also demonstrate that the 1DVAR retrieval algorithm with updating LSE approach could reduce the dependence of soundings on the emissivity first guess and improve the sounding accuracy. Furthermore, this study might provide some insights into retrievals from future advanced IR sensors by using the current IR LSE datasets. Last, the retrieved emissivities over ocean reveal angle dependence that is consistent with that from the ocean emissivity model. This result indicates that the algorithm for retrieving...
profiles and emissivity simultaneously is reliable, and this technique could be adapted for assimilating radiances over land.

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